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*Published in:*  
Energy Procedia

*DOI (link to publication from Publisher):*  
[10.1016/j.egypro.2017.09.738](https://doi.org/10.1016/j.egypro.2017.09.738)

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*Publication date:*  
2017

*Document Version*  
Publisher's PDF, also known as Version of record

[Link to publication from Aalborg University](#)

### *Citation for published version (APA):*

Hansen, T. K., Peuhkuri, R. H., Møller, E. B., Bjarløv, S. P., & Odgaard, T. (2017). Material characterization models and test methods for historic building materials. *Energy Procedia*, 132, 315-320.  
<https://doi.org/10.1016/j.egypro.2017.09.738>

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11th Nordic Symposium on Building Physics, NSB2017, 11-14 June 2017, Trondheim, Norway

## Material characterization models and test methods for historic building materials

Tessa Hansen<sup>a\*</sup>, Ruut Hannele Peuhkuri<sup>b</sup>, Eva B. Møller<sup>b</sup>, Søren Peter Bjarløv<sup>a</sup>,  
Tommy Odgaard<sup>a,c</sup>

<sup>a</sup>Technical University of Denmark, Department of Civil Engineering, Brovej 118, 2800 Kgs. Lyngby, Denmark

<sup>b</sup>Danish Building Research Institute, Aalborg University, A.C. Meyers Vænge 15, 2450 Copenhagen SV, Denmark

<sup>c</sup>COWI A/S, Parallelvej 2, 2800 Kgs. Lyngby, Denmark

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### Abstract

Predictions of long term hygrothermal performance can be assessed by dynamic hygrothermal simulations, in which material parameters are crucial input. Material parameters for especially historic materials are often unknown; therefore, there is a need to determine important parameters, and simple ways for estimation of these. A case study of a brick wall was used to create and validate a hygrothermal simulation model; a parameter study with five different parameters was performed on this model to determine decisive parameters. Furthermore, a clustering technique has been proposed to estimate decisive parameters through simple testing of interrelated parameters that are easier to determine.

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Peer-review under responsibility of the organizing committee of the 11th Nordic Symposium on Building Physics.

**Keywords:** Historic building materials; hygrothermal simulation; moisture; material characterization; test methods

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### 1. Introduction

In historic buildings with façades of cultural and preservation worthy values, interior insulation is the only measure to decrease heat loss through the exterior walls. The mounting of interior insulation may introduce moisture risks. Hygrothermal simulations are therefore valuable tools in the design of a suitable interior insulation system. Hygrothermal simulations take into account many specific variables for each case in question, e.g. climatic conditions, geometry and material parameters. This study has focus on material parameters and their importance in regards to said

\* Corresponding author. Tel.: +45 45251803.

E-mail address: [tekhan@byg.dtu.dk](mailto:tekhan@byg.dtu.dk)

hygrothermal simulations. Materials used in historic buildings are extremely varied, not only in the raw materials and resources used, but also in the production method. If it can be proven that certain material properties are decisive for the hygrothermal performance and they can be determined feasibly in regards to both time and economy, it would be beneficial for future analysis of retrofit measures.

As there are numerous uncertainties in hygrothermal simulation, identification of potential discrepancies in material properties and boundary conditions were determined in a sensitivity analysis performed by Kloda [1]. The analysis concluded vital influence on output from parameters such as solar radiation absorption coefficient, thermal conductivity, suction curve, capillary conductivity and surface heat transfer coefficients. Probabilistic methods have previously been introduced by e.g. Zhao et. al. [2] and Holm et. al. [3], running 400 and 69 hygrothermal simulations respectively, for determination of the influence of material parameters and boundary conditions, and measurement uncertainties respectively. The findings of these measures were, among others, that the effect of single parameters may be seasonal, and can have both positive, negative and seasonal-dependent correlations. The studies emphasize the need for full and exact material properties for achieving valid results. By means of statistical tools however, it may be possible to attain reliability ranges for results, and simplifying the models by clustering of materials.

This paper aims to clarify the importance of the single material parameters in regards to characterization of historic building materials with limited information. It is a step towards for better prediction of hygrothermal performance by finding a linkage between clustering and simple experimental methods for material characterization.

## 2. Material Characterization

A major challenge in hygrothermal simulations of walls in historic buildings is to establish necessary knowledge of the material parameters. Material characterization is in the following described as a combination of the experimental and theoretical approach.

### 2.1. Practical determination of material properties

There are number of well-defined and standardized methods for determination of many material properties in laboratory. The methods for determination of the parameters included in this study are seen in Table 1.

Table 1: Test methods for determination of some material parameters.

Parameter	Standard method	Alternatives
Density	EN 772-13:2002 [4]	EN 1936:1999 [5]
Open porosity	EN 772-3:1998 [6]	EN 1936:1999 [5]
Thermal conductivity	EN 12664:2001 [7]	ISOMET Heat Transfer Analyzer
Water uptake coefficient	ISO 15148:2002 [8]	Plagge et. al. [9], automatic logging system
		Hendrickx [10], estimation by Karsten tube
Water vapour diffusion resistance factor	EN ISO 12572:2001 [11]	Bertelsen [12], considering moisture content dependency

### 2.2. Theoretical hygrothermal models

Moisture transport in porous media, e.g. building materials, is driven by material characteristics as well as external factors. Driving forces include gradients in partial vapour pressure, total air pressure and external total pressure, as well as gravity and pore width, defining the capillary suction [13]. Moisture transport in a material also depends on the moisture storage potential, which in turn is dependent on specific material characteristics; e.g. water retention curve relates to the porosity, effective and capillary saturation – depending on the hygroscopic range, and the function for liquid water conductivity depends on both effective saturation and water uptake coefficient. Material functions are vital as they describe properties at various conditions, therefore material functions are implemented in hygrothermal simulations together with constant material parameters. Some of the material parameters and functions are not directly measurable and therefore the process of determining the parameters also requires a calibration, either experimentally and/or numerically [14]. Simplified, the process of the material characterization can be seen in Figure 1;

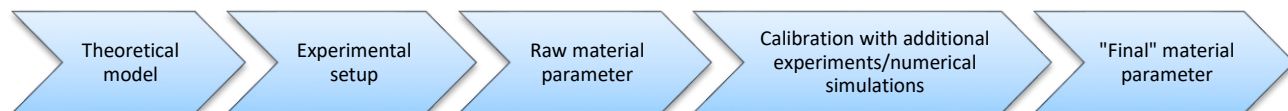


Figure 1: Flow chart of material characterization process.

### 2.3. Decisive material parameters and clustering

In hygrothermal simulations some material parameters are more decisive than others and some are interrelated. Unfortunately, some decisive parameters may be difficult to determine, however, if the interrelated parameters are easier to estimate, it might be possible to estimate the decisive parameters through simple tests. Some materials have similar pore systems e.g. most historic building materials have open pore systems, which means that, density and open porosity are interrelated. Parameter studies, like the one described in this paper, are useful when determining which parameters are decisive, while determination of which parameters are interrelated can be done by making a statistical analysis on material parameters from materials where these are already known. The purpose of a statistical analysis is twofold:

- Determination of correlations between material parameters, in this way it will be possible to see which parameters can be estimated through other parameters that are easier to determine.
- Clustering of materials. Within groups of materials e.g. bricks there can be significant differences in hygrothermal properties. By defining decisive properties and analysing how materials differ, it is possible to cluster specific materials in groups and create generic material representing the cluster.

The work of Zhao et. al. [15] investigates different clustering techniques, and methods for deriving a generic material from a cluster. They emphasize that it is important to have found correlations between parameters first, otherwise some parameters will have too big an influence on the clustering. Generic materials can be used to overcome the problem of incomplete material data. Zhao et. al. [16] have also developed a concept for the inclusion of input uncertainties and a stochastic material database for probabilistic simulation rather than deterministic. Including the probability distributions of material properties, gives better estimations of the realism in achieved hygrothermal simulation results.

## 3. Method

### 3.1. Case study

For investigation of the importance in variation of various material parameters, a case study is used. The case study is a wall consisting of merely of brick and mortar. The wall is 1½ brick thick (348mm) and is internally rendered with 12-15mm of the same lime mortar used in the joints. The bricks used are new yellow softmolded bricks from Helligsø Teglværk, and the mortar for joints and rendering is a 7.7% lime adjusted wet mortar with grain size 0-4mm (air lime) which was produced to resemble characteristic mortar from year ~1900 in Denmark. The wall is built in a container wall with several other test walls, located in Kgs. Lyngby, Denmark, and the external side of the wall faces the actual climate, towards southwest. The interior conditions are set to be constant at 20°C and 60 % relative humidity, however natural fluctuations occur, e.g. no cooling system during warm periods. Temperature and relative humidity sensors are located in the wall at three locations, as seen in Figure 2. The sensors used are HYT-221 sensors, logging data every 10 minutes. Furthermore, temperature and relative humidity sensors are located on both external and internal side of the wall, for monitoring of boundary conditions.

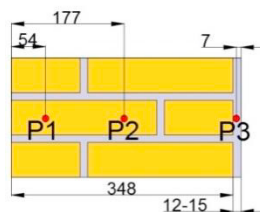


Figure 2: Cross section of wall, and indication of sensor locations. Exterior climate is on the left.

### 3.2. Hygrothermal simulation

As 1D simulations are presented, the mortar joints are not included in the models. The model consists of 348mm brick, and 15mm mortar on the internal side. Material parameters for simulations are based on [17]. Local climate measurements from DTU weather station were implemented in the model. Climate data for one year, 2016, has been used and recycled for a 2<sup>nd</sup> year of simulation. Results from the 2<sup>nd</sup> year will be presented in this paper. Initial conditions for temperature and relative humidity in the construction were set as the measured values in 3 points, for each 1/3 of the construction thickness. The simulations are performed in the hygrothermal simulation software Delphin [18], and will constitute the base for the investigation of the significance of the various material parameters. Therefore

the base model must first be validated with measured data. Hereafter a variety of simulations can be made with variations in material parameters, in order to establish the effect on the obtained simulation results.

### 3.3. Variation of material parameters

To investigate the importance of the various basic material parameters, simulations with  $\pm 10\%$  values were made for the following brick parameters; density, open porosity, thermal conductivity, water uptake coefficient and water vapour diffusion resistance factor. The alterations in some of the constant parameters effect some material functions in Delphin (e.g.  $A_w$  scales the liquid water conductivity). The implemented values, are shown in Table 2. Although some of the parameters are interrelated, e.g. thermal conductivity increasing with an increased density and decreased open porosity, the parameters are varied one by one.

For investigation of the correlation between parameters, additional simulations were made with actual material parameters provided by the Delphin database, on 2 different types of brick, with a large difference in density, see Table 2.

Table 2: Material parameter variations, and materials for simulation of correlation investigation.

	Original	-10%	+10%	High density Brick Bernhard	Low density Brick Schlagmann	Unit
<b>Density, <math>\rho</math></b>	1713	1542	1884	2060	1396	kg/m <sup>3</sup>
<b>Open porosity, <math>\theta_{por}</math></b>	0.38	0.34	0.41	0.25	0.47	m <sup>3</sup> /m <sup>3</sup>
<b>Thermal conductivity, <math>\lambda</math></b>	0.52	0.47	0.57	1	0.27	W/mK
<b>Water uptake coefficient, <math>A_w</math></b>	0.2	0.18	0.22	0.10	0.44	kg/m <sup>2</sup> s <sup>1/2</sup>
<b>Water vapour diffusion resistance factor, <math>\mu</math></b>	25	22.5	27.5	19	14	-

## 4. Results

### 4.1. Practical measurements, simulations and validation of model

Various simulations were run to establish a model validated through measurements. The combination of uncertainties in measurement and simulation, as well as unknown factors makes it difficult to achieve a simulation model 100% in accordance with measurements, especially for point P2; however a model considered validated continuous use in this work was obtained. With this validated model, the further simulations with material parameter variations become were performed.

### 4.2. Variation in material properties

Results from the simulations with varying material parameters, yield various results. Variations in density and open porosity alone show no effect to the results. In P1 and P2, variations in  $A_w$  and  $\mu$  have an effect on relative humidity – especially in the fall season. A decreased  $A_w$  or an increased  $\mu$  leads to increased relative humidity, and vice versa.  $A_w$  shows the largest impact on results. Thermal conductivity has a slight impact on temperature and relative humidity results in both P2 and P3; as the thermal conductivity is increased, the temperature decreases and the relative humidity subsequently increases – this effect is seen all year for P3.

Figure 3 and Figure 4 depict simulation results with the different brick types, Brick Bernhard and Brick Schlagmann from the entire 2<sup>nd</sup> year of simulation in the 3 measuring points, described in section 3.3.

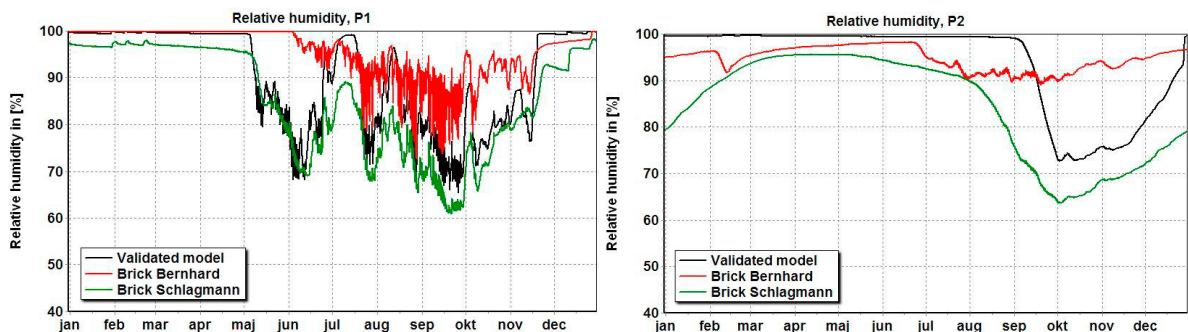


Figure 3: Relative humidity in P1 (left) and P2 (right) with different brick types.

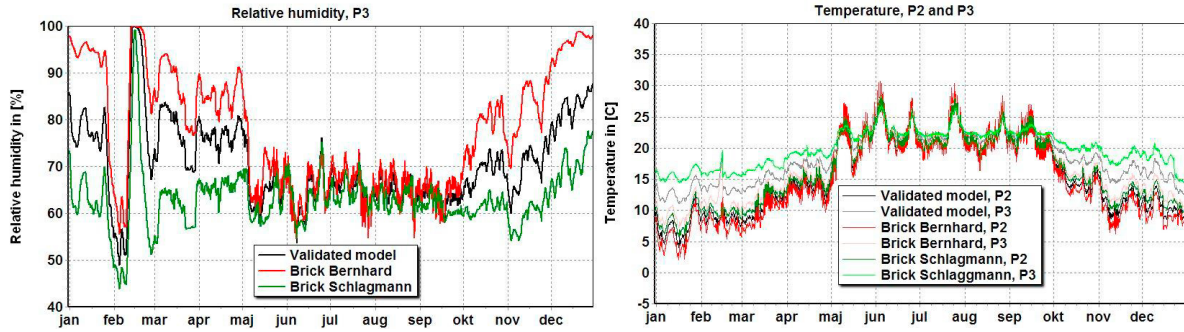


Figure 4: Relative humidity in P3 (left), and temperature in P2 and P3 (right) with different brick types.

## 5. Analysis/discussion

The validation of the simulation model does not reach a perfect fit; the simulations are performed in 1D without consideration to mortar joints, long wave emission has been omitted due to inexistent data, and exchange coefficients have been estimated. However, the validated model gives sufficient correlation in order to investigate the variations in material parameters.

Results from the various numerical simulations revealed the importance of certain material characteristics in hygrothermal conditions of a construction, while other parameters did not influence the simulation results. Table 3 gives an overview of the observed results and effects.

Table 3: Effects of variations in material parameters on the hygrothermal state of the construction.

Parameter	Significant effect	Effect
Density, $\rho$	-	
Open porosity, $\theta_{por}$	-	
Thermal conductivity, $\lambda$	T (P3), RH (P2+P3)	Increased $\lambda \rightarrow$ decreased T and increased RH
Water uptake coefficient, $A_w$	RH (P1+P2)	Decreased $A_w \rightarrow$ increased RH in colder periods
Water vapour diffusion resistance factor, $\mu$	RH (P1+P2)	Increased $\mu \rightarrow$ increased RH in colder periods

The simulations indicated that the water uptake coefficient (liquid transport) yields the largest impact on the relative humidity in both the external and middle part of the wall. The seasonal dependency can be explained partly by rain events not succeeded by fast drying from the solar radiation during summer. The influence of  $\mu$  is partly explained by the reduced drying potential due to the increased diffusion resistance. The results are in consistency with findings in [1], with the exception of  $\mu$ 's influence which was not found in their analysis.

The studied case is a brick wall with a given orientation and boundary conditions. Especially orientation of the wall, which in this case is the “worst case”, i.e. South-West orientation with heavy load of driving rain, may be a determining factor for the current conclusions. Another series of simulations with a less exposed orientation may result in a different conclusion.

The material parameter variation study was performed relatively simplistic, i.e. studying a single parameter at a time and the correlation of parameter variation was not included. In reality, many of the parameters correlate: e.g. thermal conductivity will normally decrease for decreasing density, which again decreases for increasing porosity. So the observed negligible effect of density and porosity within the +/- 10% variation on the temperature and moisture conditions in the studied construction must be linked to the observed significant effects of  $\lambda$ ,  $\mu$  and  $A_w$ , as these are functions of density and/or porosity. For this reason, further simulations were performed with 2 different types of brick. The results showed that the denser type of brick, Brick Bernhard, yielded results of higher relative humidity. The water uptake coefficient is lower in this brick type, underlining the effect demonstrated by the previous simulations. The lower relative humidity in Brick Schlagmann, can partly be explained by the increased temperatures. In Figure 4 it is apparent, that the material characteristics are dominantly influential in colder periods.

The simulations with Bernhard and Schlagmann bricks illustrate how different the outcome of hygrothermal simulations can be, depending on which brick was chosen for the simulation. Therefore the planner should not just choose any brick, but a correct brick type. A study of 23 specific bricks by Zhao et. al. [15] resulted in four different clusters; New bricks, Historical bricks of clay and loam, Historical bricks of clay, loam and sand and Bricks for external facades (high density and low moisture storage and transport capacity).



Therefore, information already available, e.g. construction period, or information on either density or transport capacity estimated by simple tests, e.g. Karsten tube, could be sufficient for determination of the correct cluster for better estimation of the hygrothermal performance.

## 6. Conclusion

For variations of +/-10%, the density and open porosity yielded no change in results for temperature and relative humidity. Water uptake coefficient, water vapour diffusion resistance factor and thermal conductivity all yielded results indicating seasonal impact on the effect of the various parameters. The water uptake coefficient turned out to be the most influential factor on relative humidity, of the parameters investigated. The seasonal variations indicate the material parameters dependency on external factors and conditions. If the water uptake coefficient can be estimated, or even just categorized, by use of Karsten tube, it may valuable information in regards to characterization of historic materials and hygrothermal simulations with clustered materials.

## 7. Acknowledgements

The presented work is a part of RIBuild project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 637268.

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